RELAP5-3D with PHISICS Neutronics, Part 2 – Transient Analysis

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The algorithm for transient analysis with PHISICS-RELAP5 coupling

This is the second part of a three-part article on the newly developed PHISICS code and its coupling with the RELAP5-3D. It focuses on the transient analysis coupling scheme. While this is a standard scheme already present in the coupling with NESTLE, more capabilities are added by the usage the PHISICS package. In the following the set of equation solved and the software flowchart will be presented and discussed.

Computer Environment

As already discussed PHISICS takes full advantage of massively parallel architectures, deploying an implementation of the MPI protocol. This is especially beneficial when a detailed simulation, allowed by the new package, might require long computational time. It is important to notice that the solution of the diffusion/transport equation might suffer from loss of performance due to the communication cost between nodes while this is completely absent when referring to the cost of interpolating cross section in multidimensional tables. In fact, when using PHISICS this might be very expensive due to the possibility of directly using microscopic cross sections.

Subsystems of PHISICS

We briefly describe here the modules that are required in this specific scheme:

- INSTANT is the name given to the portion of the PHISICS package that solves for the neutron flux and fission power spatial distribution using the transport (diffusion as a special case) equation and fission power normalization (here needed only to set up the initial condition).
- MIXER is the portion that performs table look-ups, based on the TH field (and possible other parameters like burn up or xenon concentration), to generate the discrete Fission and transport operators. It operates indifferently on microscopic and macroscopic cross section and a mix of those.
- MRTAU is the depletion module that solves the Bateman equation to model the burn-up and natural decay of the nuclides.
- The Time Integrator in same sense could be seen as a preprocessor for the transport solver that applying a second order fully implicit Euler scheme recast the time dependent problem in a source like problem. This transformation is accomplished by the introduction of an additional component of the absorption cross-section and the arising of an external source. In the external source it is embedded also the contribution from the delayed neutrons. The delayed source is constructed by exact integration of the decay equation for the precursors after an operator split is used to remove the dependence from the future value of the fission rate from the equation.

All the equations solved are illustrated in the below summary boxes suing a compact operator based formalisms (superscripts are used to indicate the time step index).

$$\begin{cases} 1) T^{i+1} = T[A^{i+1}, \Delta t] \\ 2)\ d^{i+1} = D^{i}\left[\psi^{i}, d^{i}\right] \\ 3)\ \psi^{i+1} = T^{i+1}\left[\psi^{i}\right] + d^{i+1} \\ 4)\ P^{i+1}(\vec{r}) = \alpha F^{i}\left[\psi^{i+1}\right] \\ 5)\ Th^{i+1} = f^{i+1}\left[P^{i+1}\right] \\ 6)\ B^{i+1} = Tab\left(Th^{i+1}, N^{i}\right) \\ 7)\ N^{i+1} = B^{i+1}\left[\psi^{i}\right] \\ 8)\ A^{i+1} = Tab\left(Th^{i+1}, N^{i+1}\right) \\ 9)\ F^{i+1} = Tab\left(Th^{i+1}, N^{i+1}\right) \\ 10)\ D^{i+1} = Tab\left(Th^{i+1}, N^{i+1}\right) \\ 11)\ t \rightarrow t + \Delta t \end{cases}$$

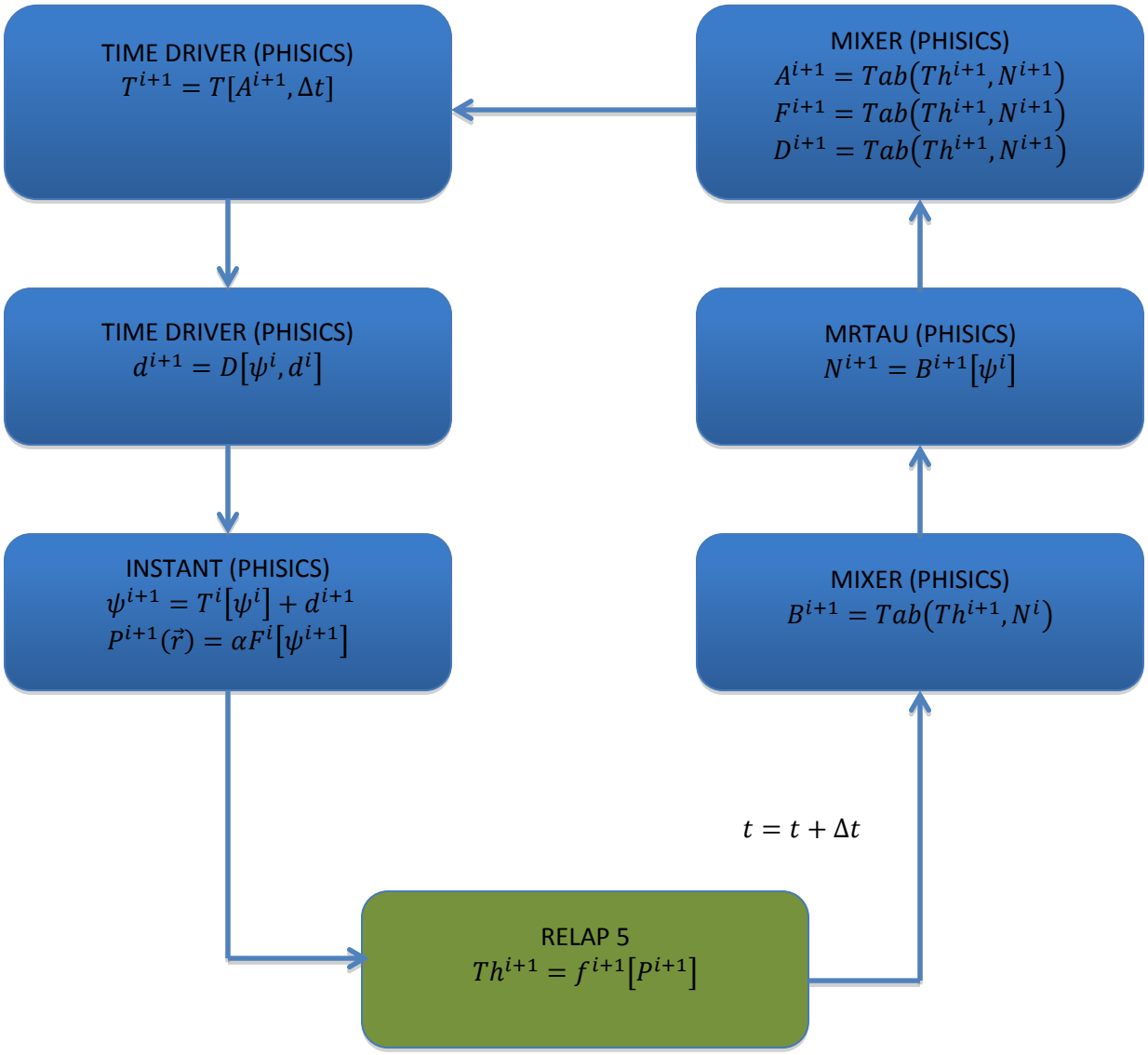
Where
d = Delayed neutron source
ψ = Neutron angular flux
D = Delayed neutron time integrator (delay fission source + decay integration)
T = Neutron flux time integrator (inverse of the transport operator plus time integration)
α = Energy by fission
F = Fission operator
p = Reactor power
Th = Thermo-Hydraulic field
f = time dependent TH plant model (inverse computed by RELAP5-3D)
N = Nuclide density
B = Inversion of the Bateman equation
Th = Thermo-Hydraulic field
Tab = Table look up

Time Dependent Marching Scheme:

In the following are described the steps that describe the marching scheme for the modeling of the time dependent behavior of the nuclear reactor plant. Point zero that is essentially the initialization of the problem is not shown in the above set of equations since not repeated at each time step and also equal to the steady state iterative scheme illustrated in the previous newsletter.

0. Initialization of the problem
   a. The steady state iterations described in "Steady State Coupling" in the previous newsletter is used to determine K_{eff} for a given power level. This requires the restart capability of RELAP5-3D since the code need to switch from a steady state analysis (used here) to a transient mode.
   b. The average fission operator is split in the prompt and delayed component (this require a coherent treatment of the prompt, delayed, and steady state fission yield)
   c. The fission cross sections are renormalized to start with a user provided reactivity value (default is of course zero or equivalently K_{eff} equal 1). This is done in order to avoid power drifts due to numerical error in the evaluation of criticality levels.
   d. Macroscopic cross section are prepared corresponding to the steady state solution from the tabulated micro to account for the TH field
1. The transport operator is modified to simulate the time discretization
2. The steady state delayed neutron source is computed
3. The transport time dependent source problem is solved
4. Power is computed
5. TH field is solved
6. Cross section are re-evaluated for the new TH field
7. The isotopic densities are recomputed via the solution of the Bateman Equation
   The new cross-sections are recomputed for accounting new isotopic composition and burn up level allowing the construction of the new operators:
8. Transport

9. Fission
10. Depletion
11. Time is moved forward



Final Remarks:

The introduction of a full neutronic package in the RELAP5-3D computation scheme allows accounting for a completeness of effects not available before. For example no equilibrium models are used for the description of short-lived nuclides like Xenon, Samarium and Iodine. This would be, for example necessary to model reactor power following and BWR instability where time scale of the thermo-hydraulic transient are comparable with the lifetime of such nuclides. Another interesting application of a such detail model would be the proper modeling of decay heat contribution either in shout down simulation or in power following. Currently a more detailed library of isotope paths than the one available would be necessary to precisely model decay heat but the capability in terms of development is already present in the PHISICS software.